Using CERES and Energy Budget Observations to Develop and Assess a Coupled Earth System Model: Adventures with CESM2

A. Gettelman, NCAR

Thanks to J. Fasullo & the 'CESM Development Team':

Esp: Lamarque, Bogenschutz, Hannay, Neale, Medeiros (NCAR), Liu (UWy), Larson (UWM)

NCAR NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

NASA ARM CLIMATE RESEARCH FACILITY DEPARTMENT OF ENERGY UNITED STATES OF AMERICA NSF

Theme Song

“Once in a Lifetime”

(Talking Heads)

Should be stuck in your head when I am done

Outline/Motivation

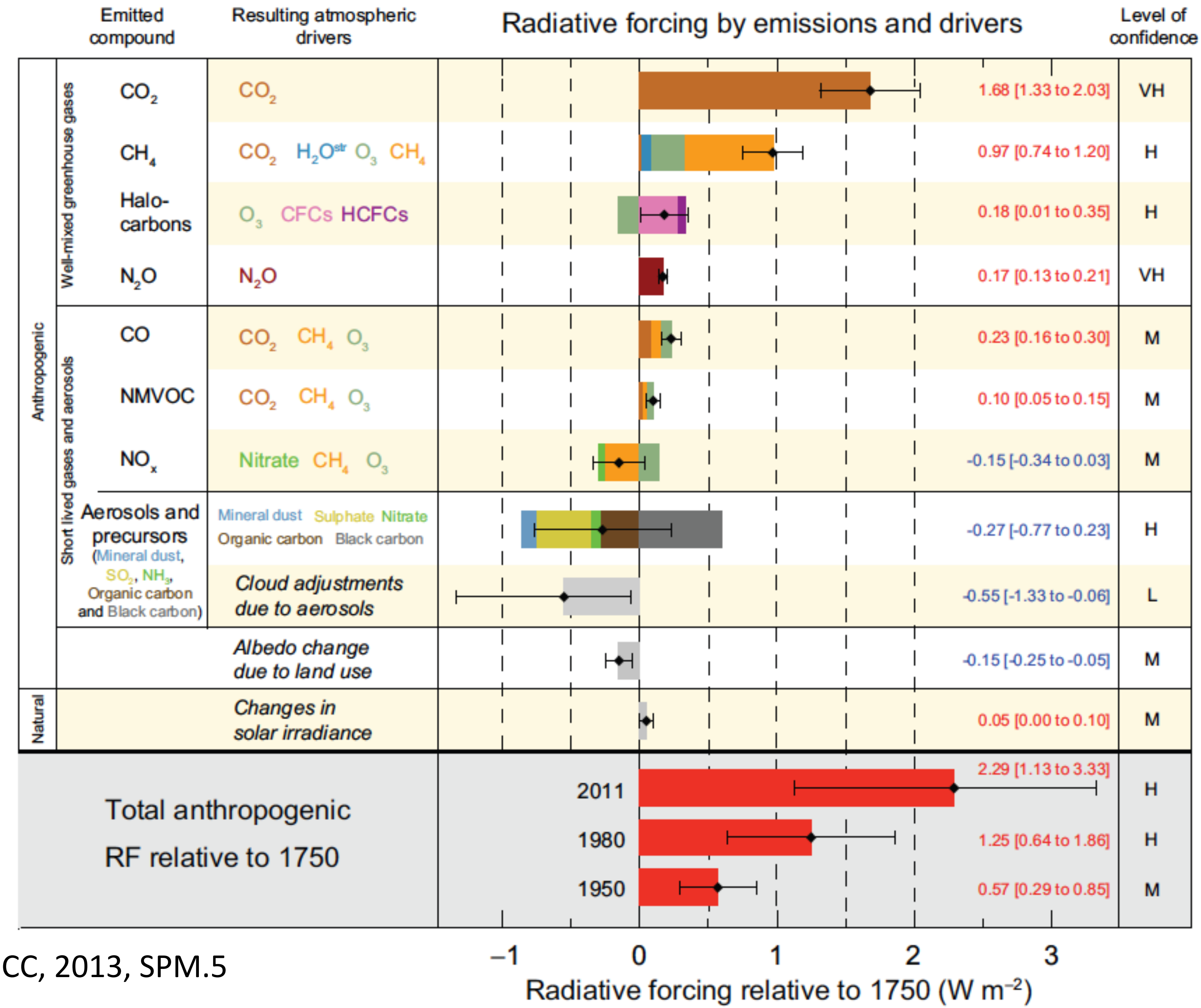
(And you may ask yourself. Where does that highway go to?)

- Understand forcing and feedbacks in CESM2
- Forcing is a balance between aerosol forcing and GHG forcing $F = F_{GHG} + F_{aero}$
- Feedbacks: response of the system
- Formally:

$$R = F - \lambda dT_s + dH$$

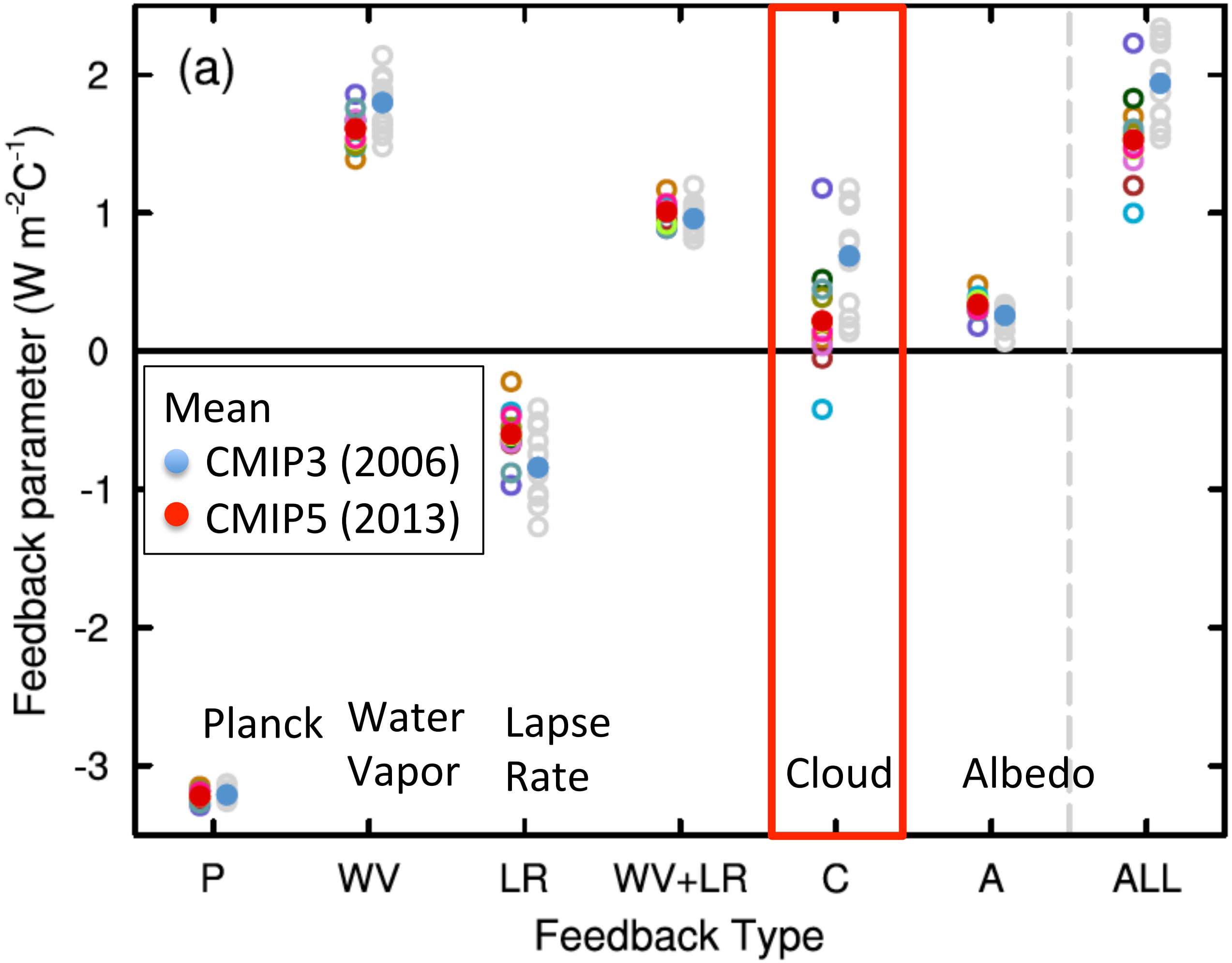
R= TOA imbalance, F=Forcing, λ= feedback parameter

H= Ocean Heat content, T_s = surface temperature



IPCC, 2013, SPM.5

Climate Feedbacks



Planck $\varepsilon = \sigma T^4$ (-)

Water Vapor
+T & RH=C → +H2O (+)

Lapse Rate (-)

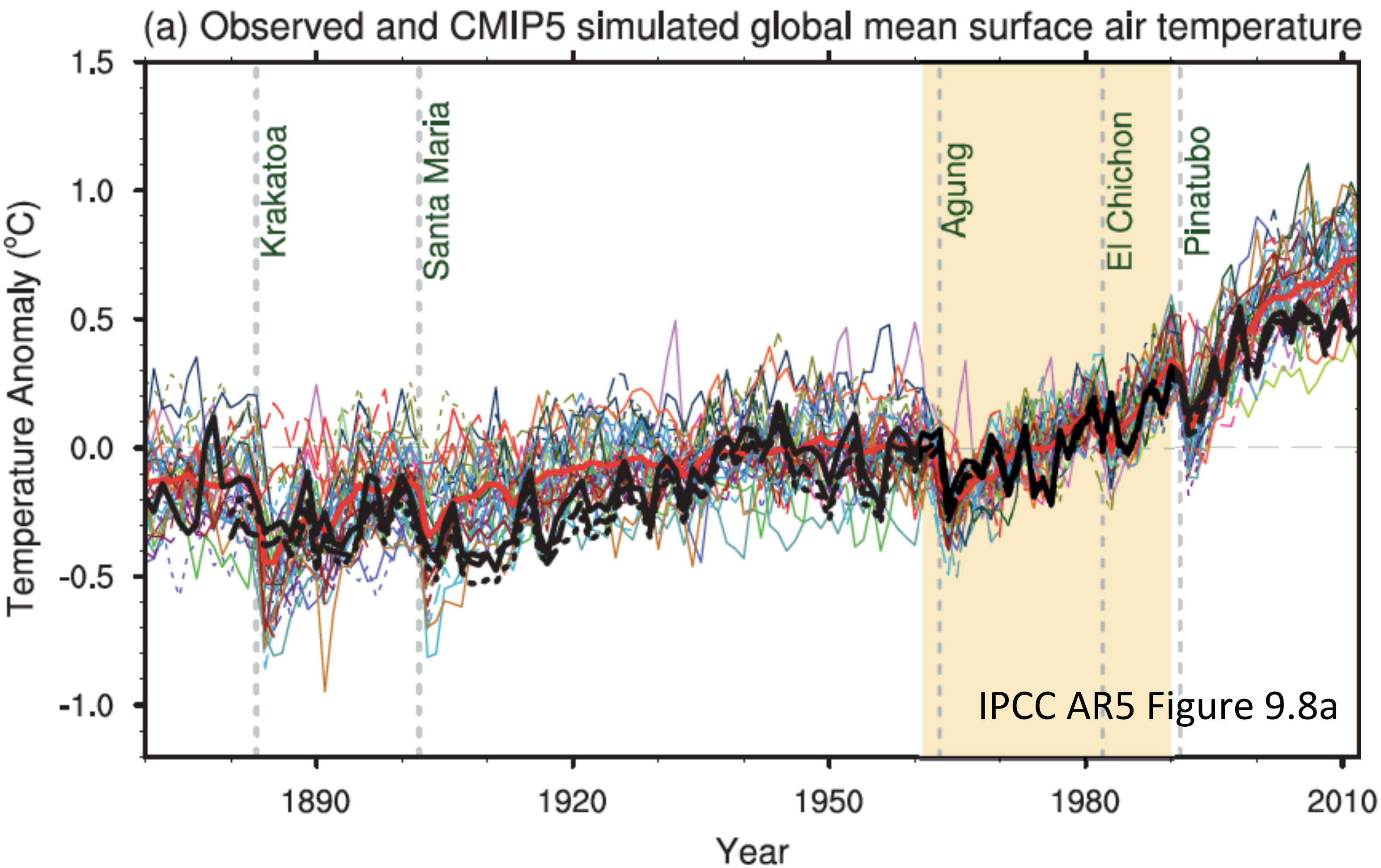
Albedo (snow, ice)
+T → less snow, ice
-T → more snow, ice (+)

Clouds: Complicated (+)

IPCC, 2013 (Ch 9, Hartmann et al 2013) Fig 9.43. Updated from Coleman 2003

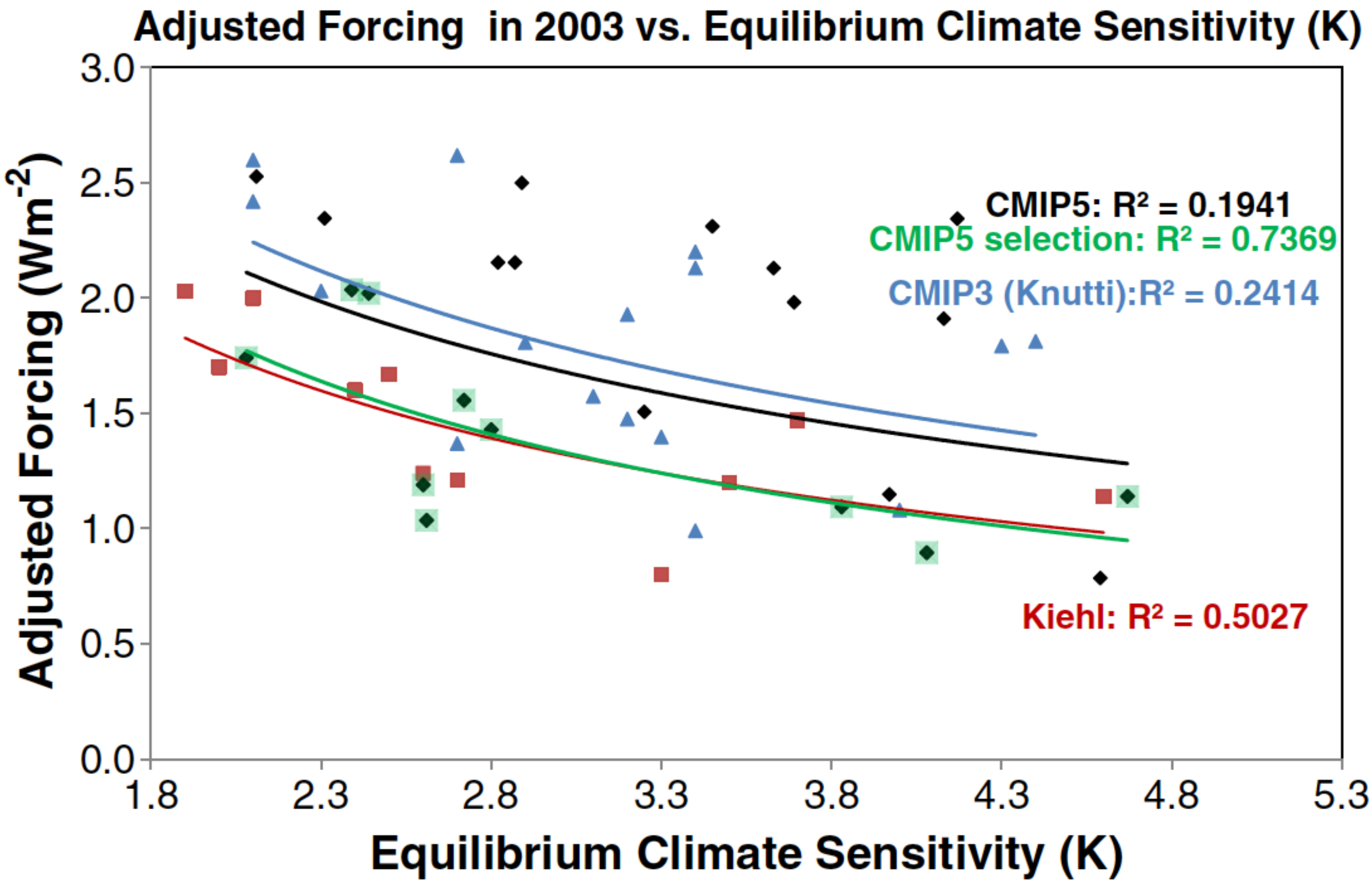
How did we get here?

$$R = F - \lambda dT_s + dH$$



Models reproduce *OBSERVED* temperature trends
Note: secret hiding in plain sight….

Forcing Uncertainty



Models that reproduce 20th Century

Forster et al 2013, Figure 7
Updated from Kiehl et al 2007

Forcing and Feedback

$$R = F - \lambda dT_s + dH$$

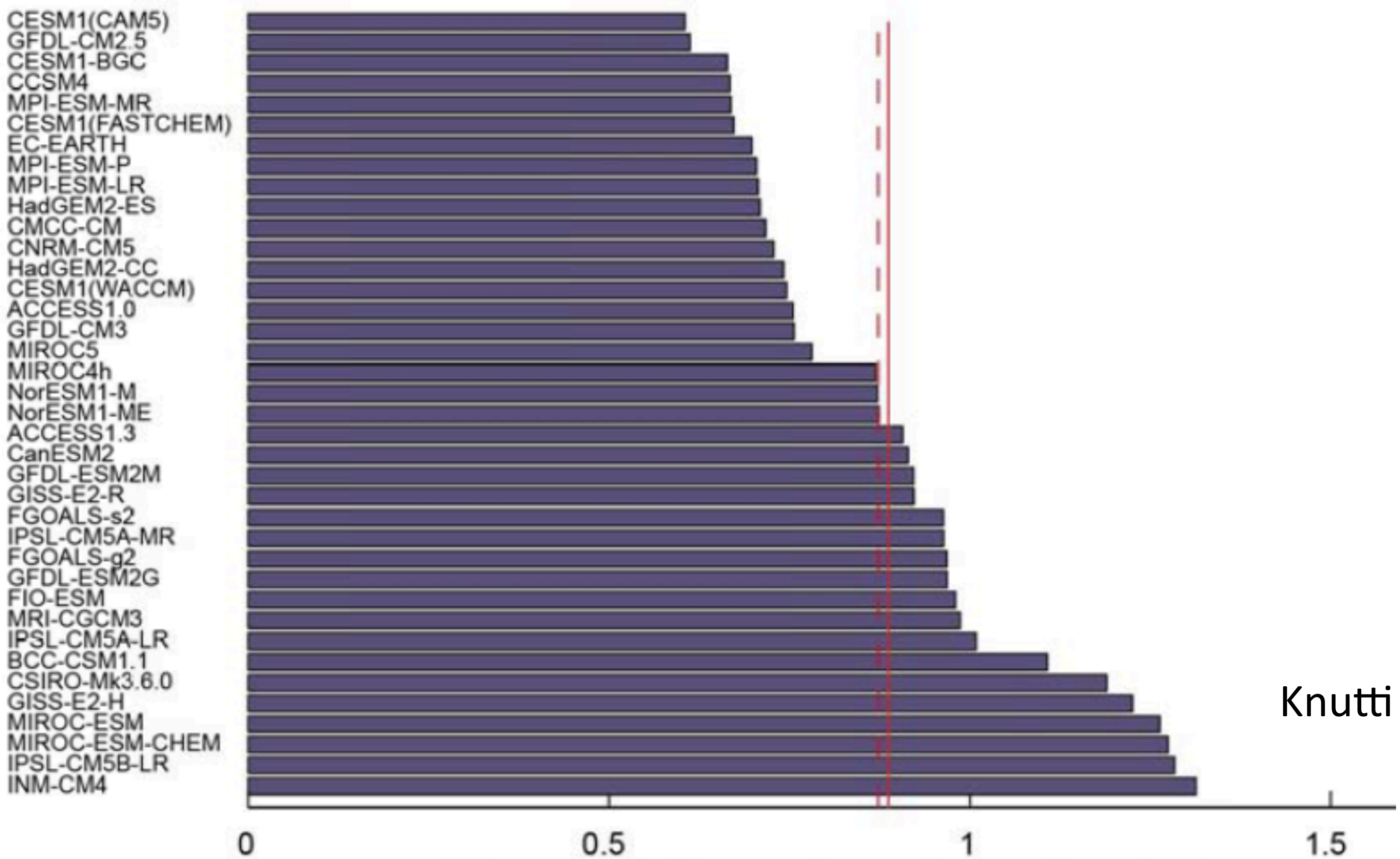
$$dT_s = (F - R + dH)/\lambda$$

$$dT_s = (F_{ghg} + F_{aero} - R + dH)/\lambda$$

- Implication is that R (TOA imbalance) is critical for understanding
- Issues with all these terms, so hard to use this to constrain λ.

You may find yourself in a beautiful house

CESM1: The "Least Bad Model of Them All"



Knutti et al 2013, GRL

Normalized distance (RMSE) from Temp and Precip 'Observations'

CESM2: Major Improvements

(New Slogan in Development)

- Reduced biases in many parts of the system
- Land Ice model (Greenland)
- Land model enables more impacts research
- Better hydrologic cycle*
- High Resolution/Regional Climate Capability
- Hierarchy of simplified models
- Physical foundations for a scale-insensitive (scale aware) model

- What specifically did we do?

**Under the rocks and stones. There is water underground.*

And you may say to yourself My God! What have I done?

- Ocean (POP2)
  - Improved mixing parameterizations
  - Estuary Model
  - Hourly coupling to atmosphere
- Sea Ice (CICE5)*
  - New thermodynamics (prognostic salinity, mushy layer)
  - Melt ponds
  - Bio-geochemistry
  - Improved Melt Water
- Land (CLM5): Improvements for impacts research
  - River routing model, Crop Model, Improved snow model.
  - Improved Carbon cycle (with N limitation)
  - Ecosystem Demography (biome boundaries, dynamic land use).
- Land Ice (CISM)
  - Greenland surface mass balance
  - Integrated with Snow and Land Model

** There is water, at the bottom of the ocean. Under the water, carry the water.*

CESM2: The CAM Family

This is not my beautiful house!

Model	CAM3 CCSM3	CAM4 CCSM4	CAM5 CESM1.0-1.2	CAM6 CESM2
Release	**Jun 2004**	**Apr 2010**	**Jun 2010**	**Mid 2017**
Microphysics	Rasch-Kristjansson (1998)	Rasch-Kristjansson (1998)	Morrison-Gettelman (2008)	Gettelman-Morrison (2015) MG2
Deep Convection	Zhang-McFarlane (1995)	ZM, Neale et al. (2008)	ZM, Neale et al. (2008)	ZM, Neale et al. (2008,2017)
PBL	Holtslag-Boville (1993)	Holtslag-Boville (1993)	Bretherton et al (2009)	CLUBB: Bogenschutz et al 2013
Shallow Convection	Hack (1994)	Hack (1994)	Park et al. (2009)	
Macrophysics	Rasch-Kristjansson (1998)	Rasch-Kristjansson (1998)	Park et al. (2011)	
Radiation	Collins et al. (2001)	Collins et al. (2001)	Iacono et al. (2008)	Iacono et al. (2008)
Aerosols	Bulk Aerosol Model	Bulk Aerosol Model BAM	3 Mode Aerosol Model Ghan et al. (2011)	4 MODE Modal Aerosol Model Ghan et al. (2011)
Dynamics	Spectral	Finite Volume	Finite Volume	Finite Volume/ Spectral Element (High Res)

= New parameterization/dynamics

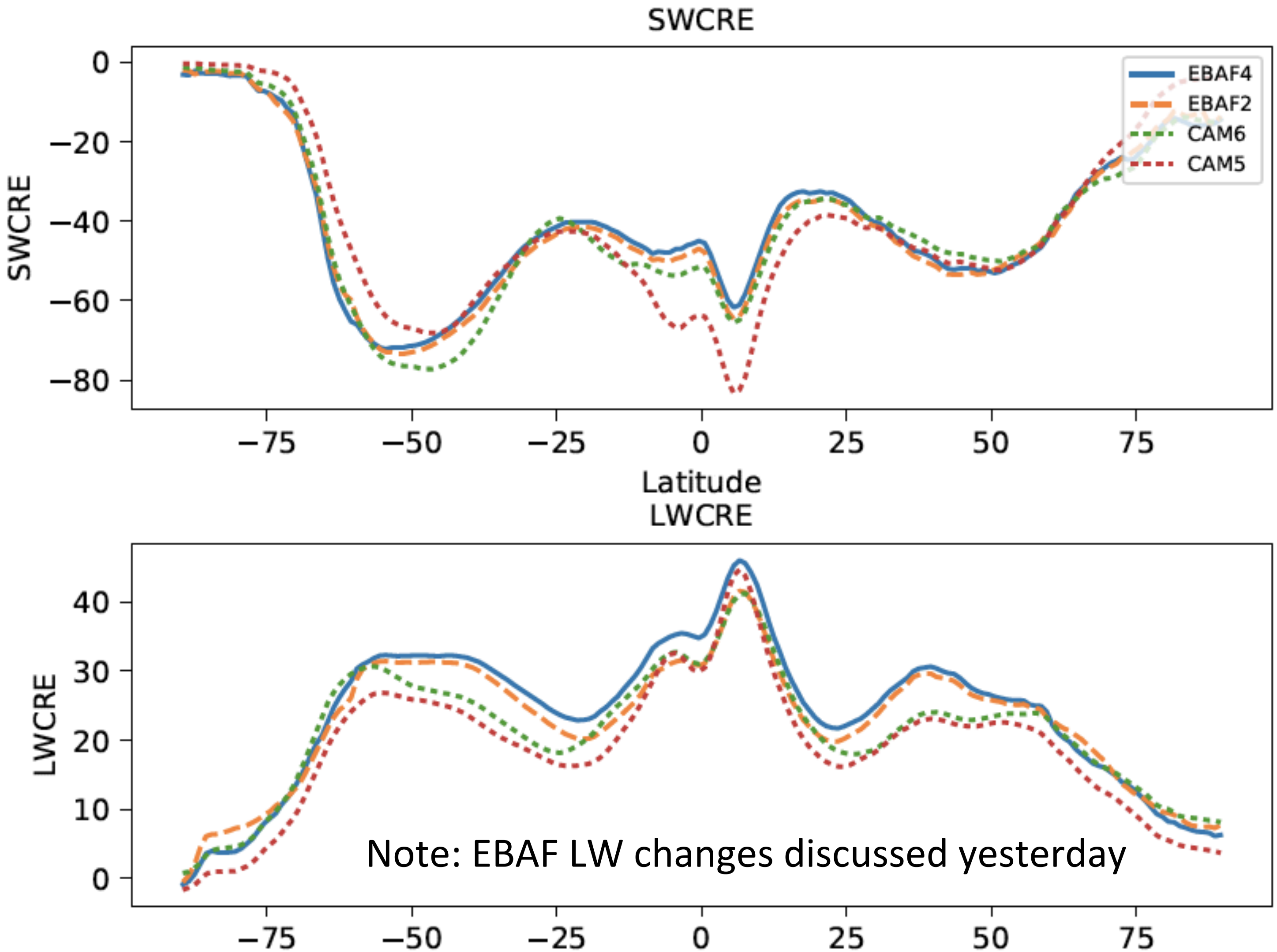
And you may ask yourself
Am I right or am I wrong?

(Model Evaluation)

- New Ice Nucleation & Mixed phase cloud microphysics has significantly reduced ASR bias in S. Ocean
- Arctic clouds have a lot more Liquid Water: Improves surface radiation balance.
- Tropical cloud biases reduced, Stratocumulus improved.

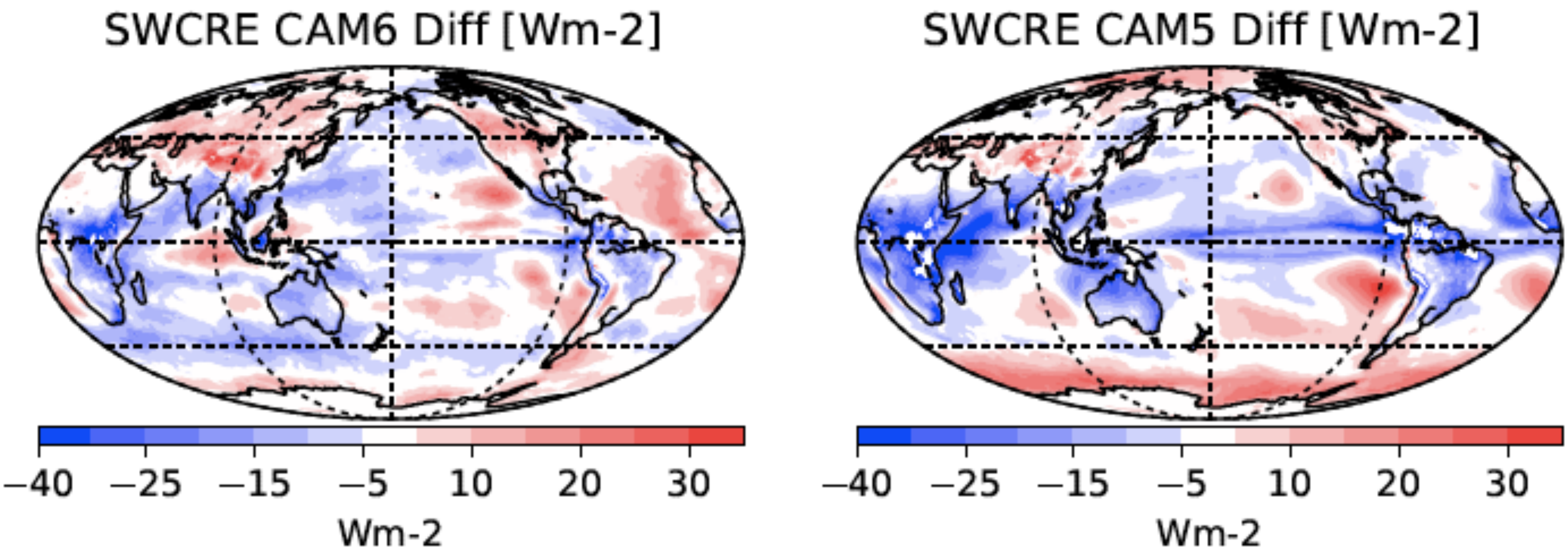
CESM2α: Results (Global)

EBAF4: *"Same as it ever was"* (with a few key changes)



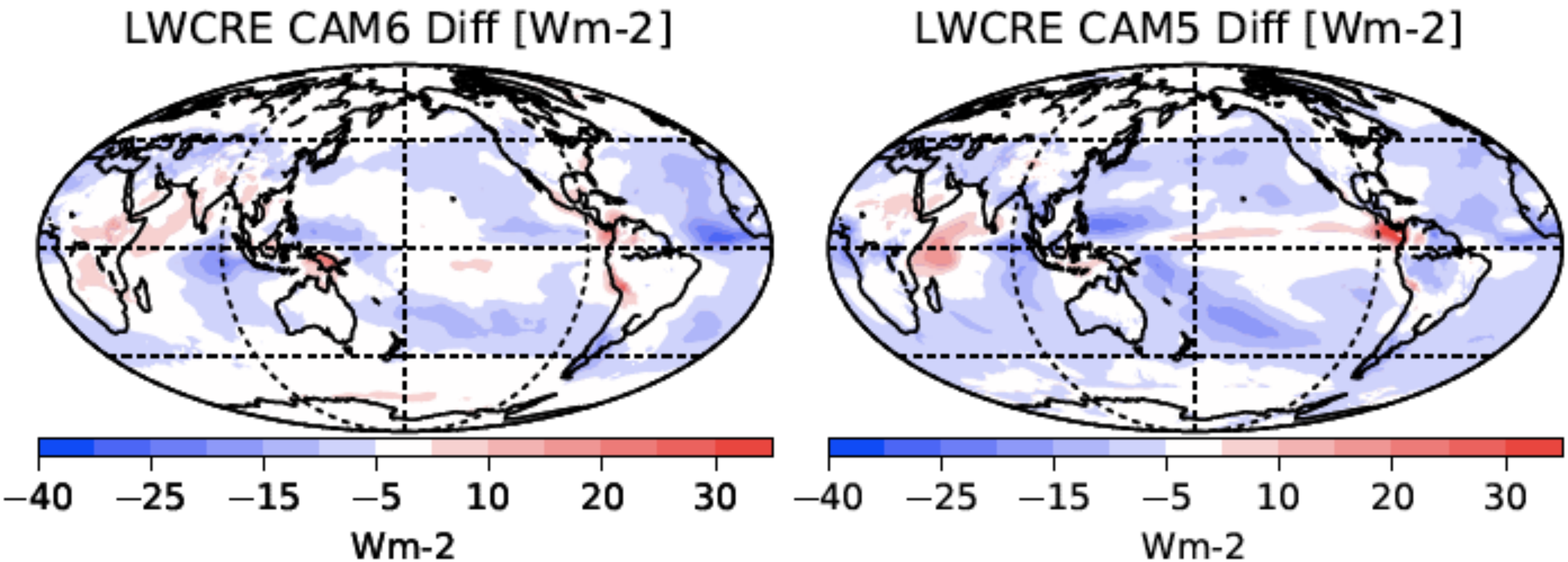
SW Cloud Biases (v. EBAF4)

Same as it ever was



LW Cloud Biases (v. EBAF4)

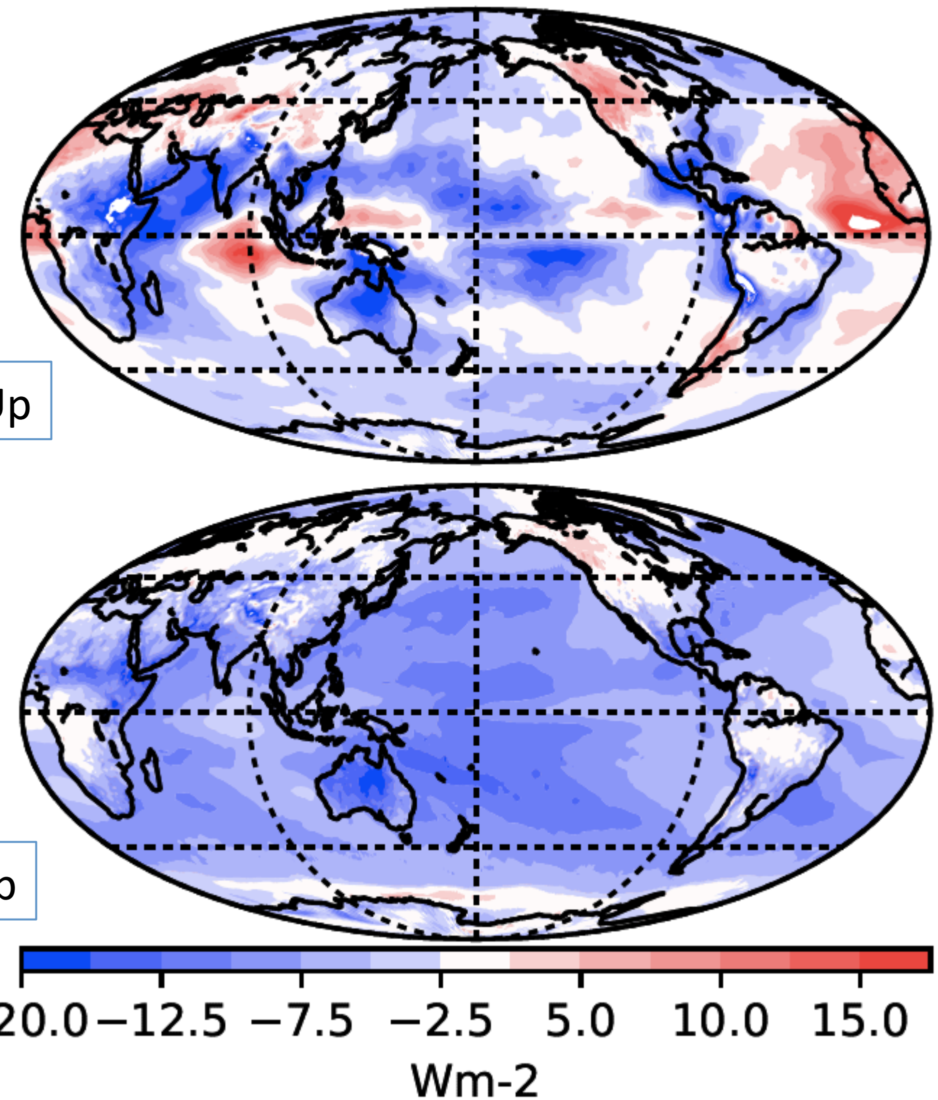
Same as it ever was



LWCRE RMSE v. EBAF4.0 = 5.38
LWCRE RMSE v. EBAF2.0 = 4.99

Note: RMSE actually larger v. EBAF4 than EBAF2.8

LW Biases (v. EBAF4)

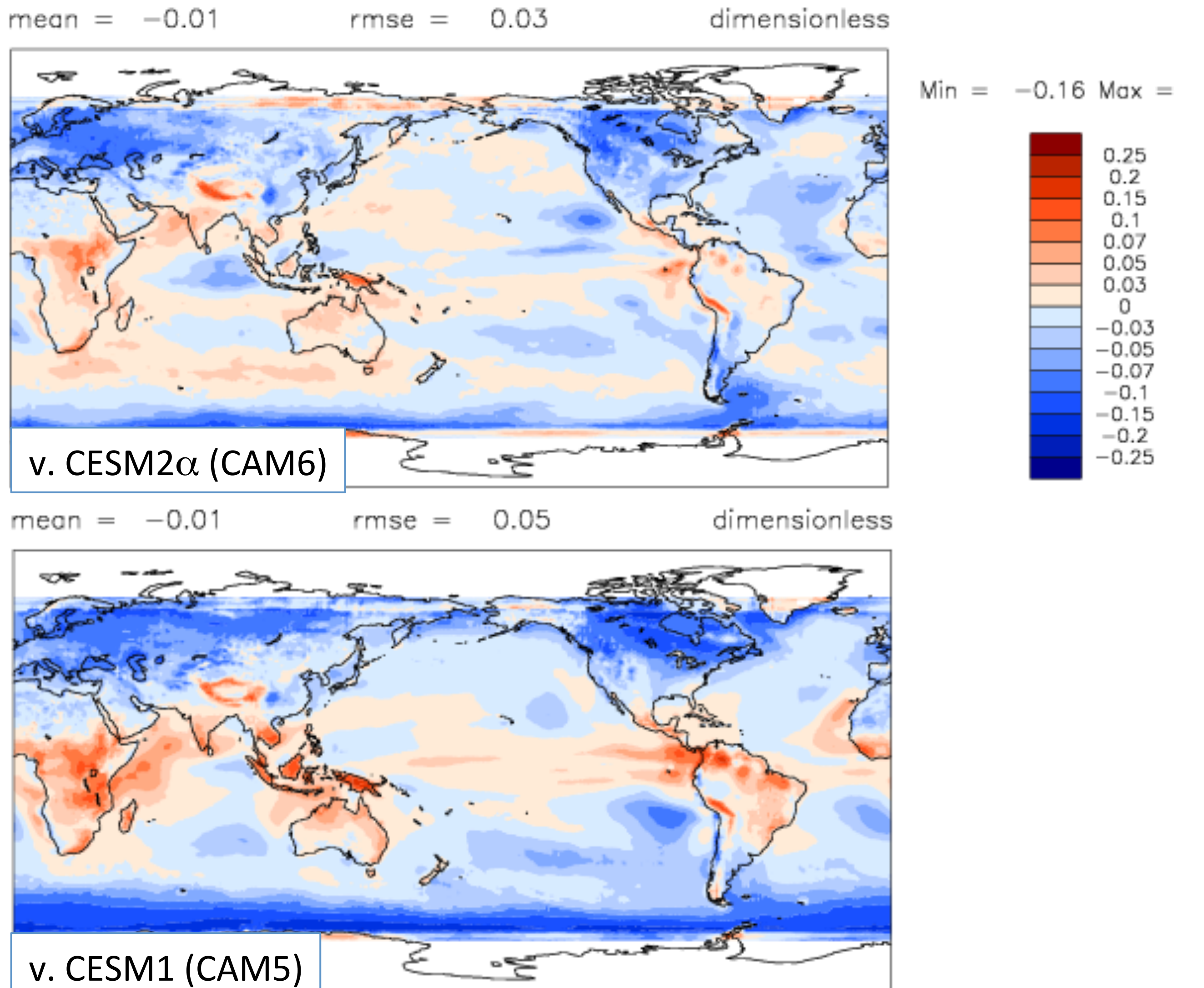


RMSE larger for LW clear than LW all
This may not be a cloud problem, but a (related) bias in water vapor.

(Remove the water,
Carry the water)

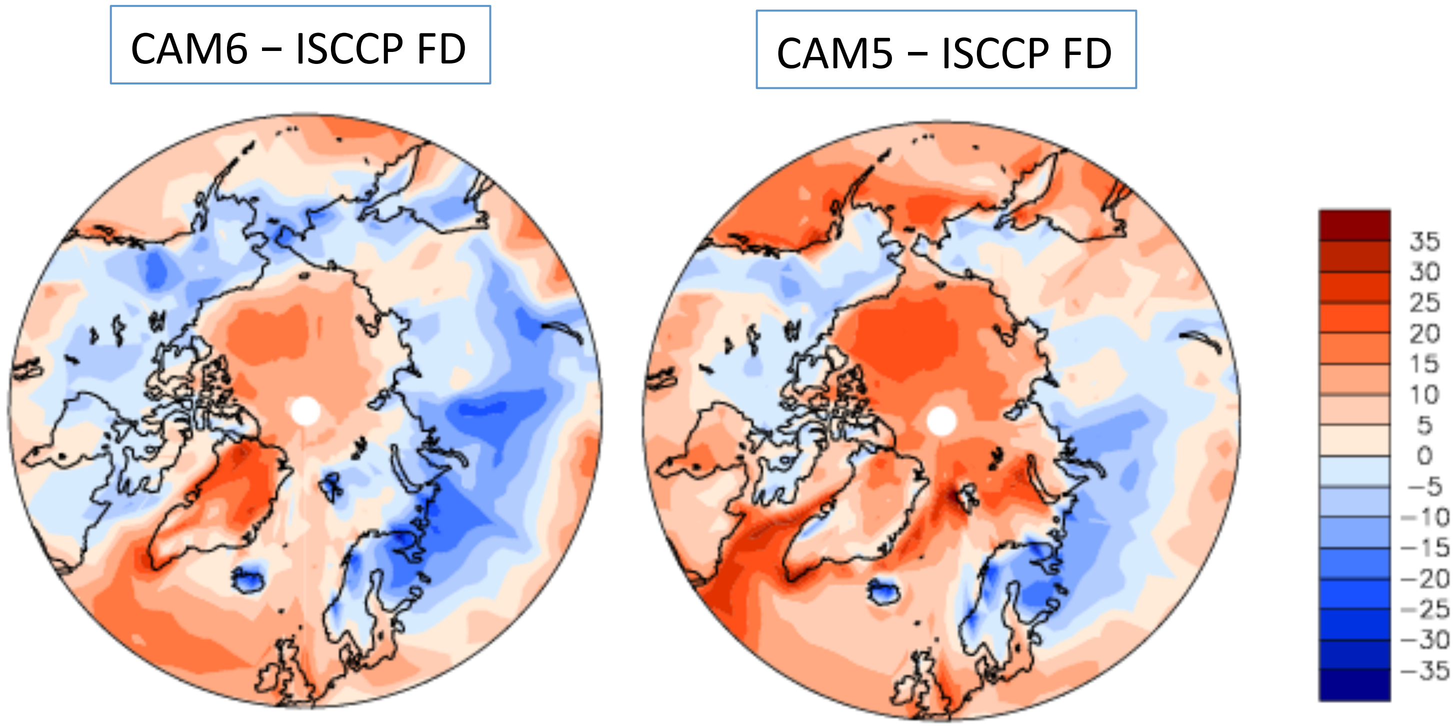
Albedo v. CERES (EBAF2.8)

Much Better…High Latitude differences Remain




(And you may find yourself
In another part of the world)

Arctic Sfc Radiation budget (DJF)



Still big biases (though observations have bias too), but improved

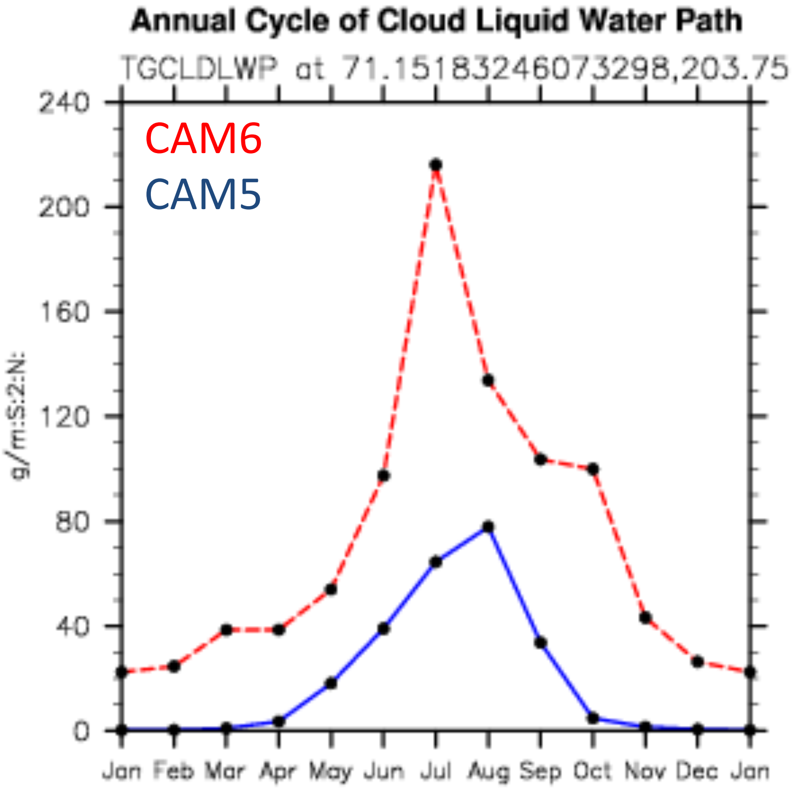
Arctic Clouds/Radiation Budget

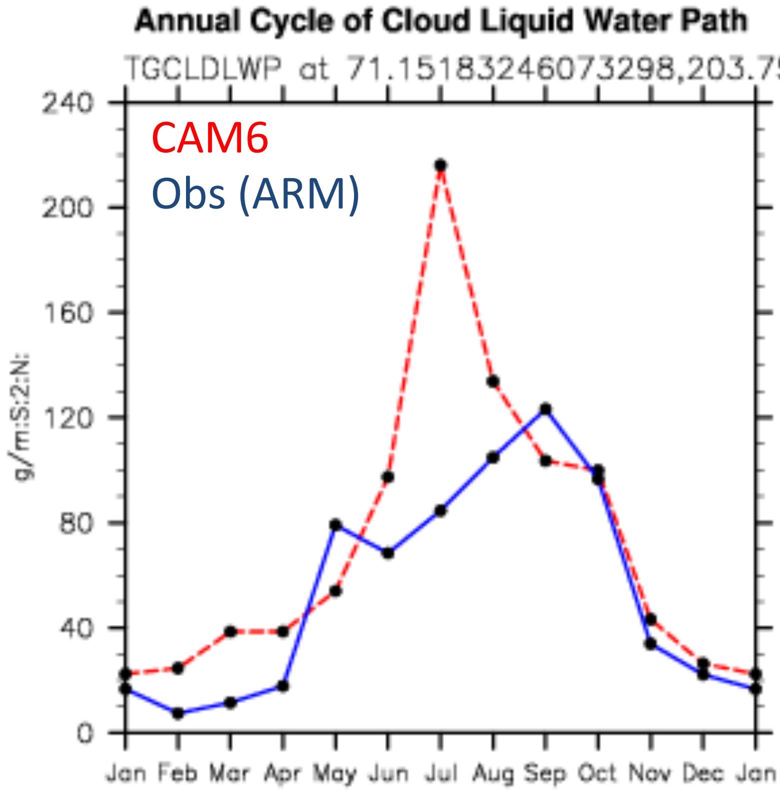
(Remove the water, at the bottom of the ocean)

- Know some things are better.
  - LWP: there is some.
- TOA fluxes (SW, LW)
- Clouds: may be missing things from Obs
  - Best is CloudSat + CALIOP. But issues with attenuation and surface clutter (lowest km)

Why? Arctic Cloud Water

ARM Barrow, AK Site





Cloud water has improved, even in winter.
Now compares well to observations.

(Water dissolving and water removing)

Forcing and Feedback Methods

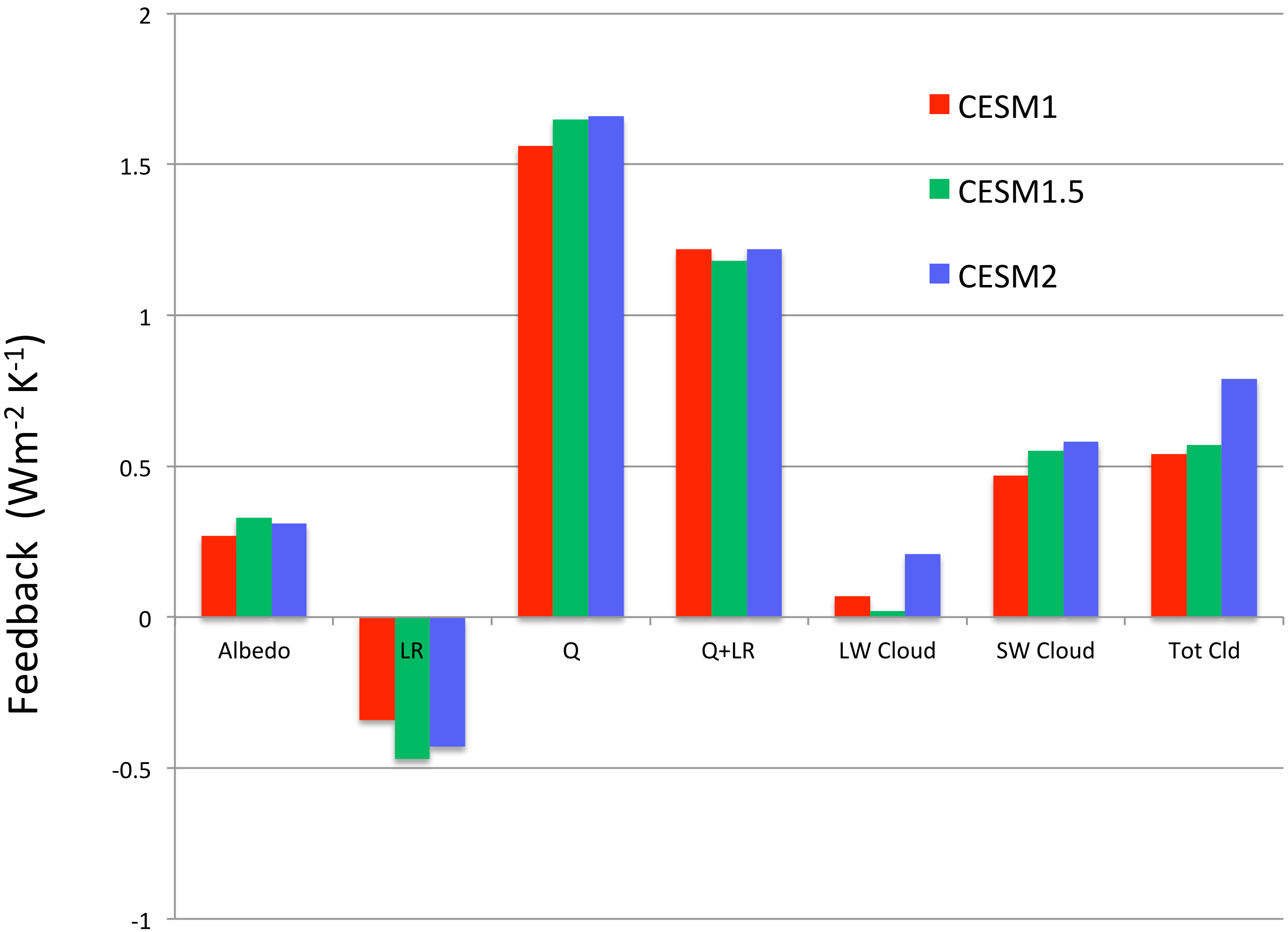
And you may ask yourself, how do I work this?

- Feedbacks: Radiative Kernels
  - Apply to Slab Ocean Model (SOM) & SST +4K simulations
  - CESM1 (CAM5)
  - CESM1.5 (Interim version)
  - CESM2α (CAM6)
- Forcing: Aerosol Forcing (total and indirect)
  - Indirect = Aerosol Cloud Interactions (ACI)
  - Use off line calculations
  - 'Clean Sky' aerosol forcing (Ghan et al 2013). Slightly higher than ΔCRE

Feedback Summary

(Same as it ever was)

From SOM Simulations

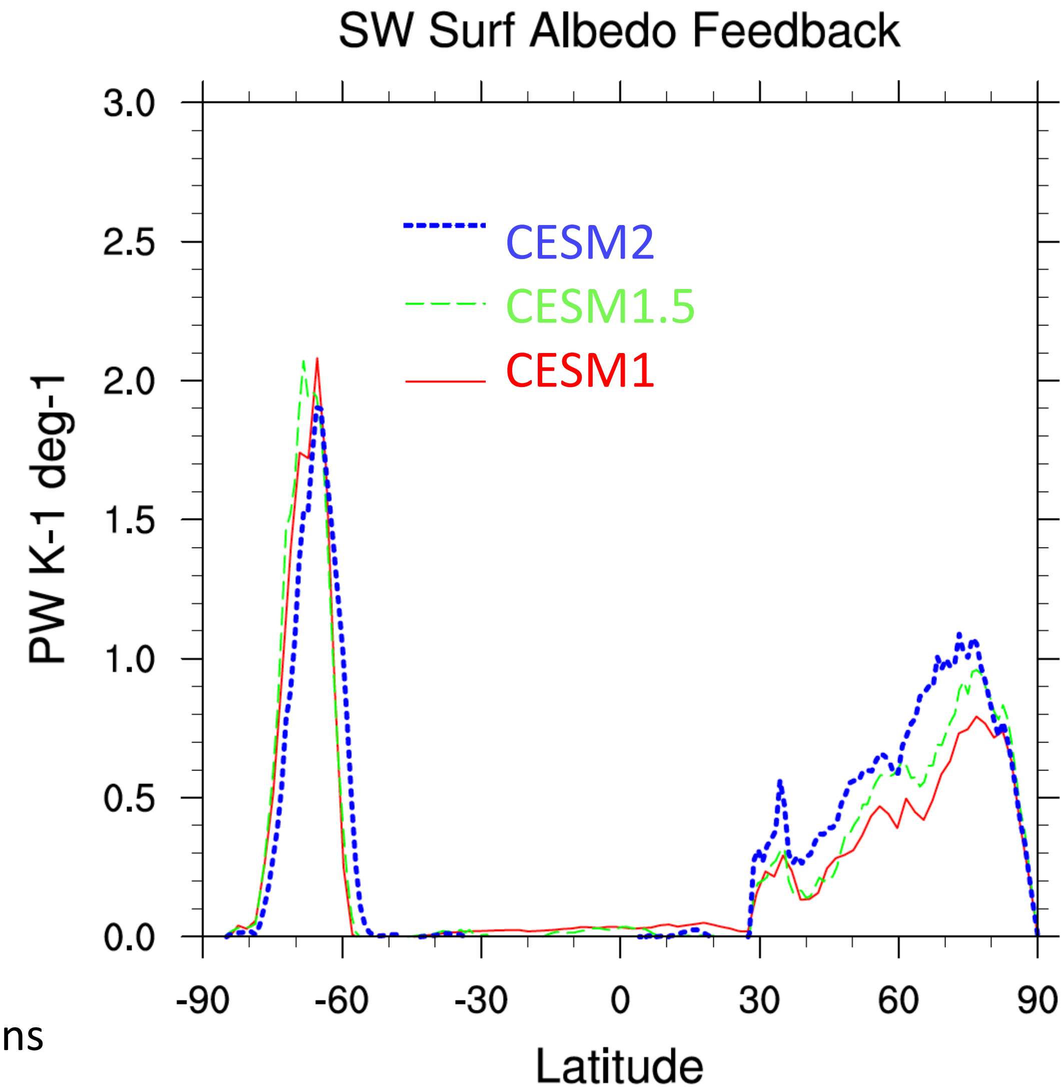


Bottom Line for Equilibrium Climate Sensitvity (ECS)

CESM1 = 4.0K CESM1.5 ≈ 3.8K CESM2 ≈ 4.0K

Surface Albedo Feedback

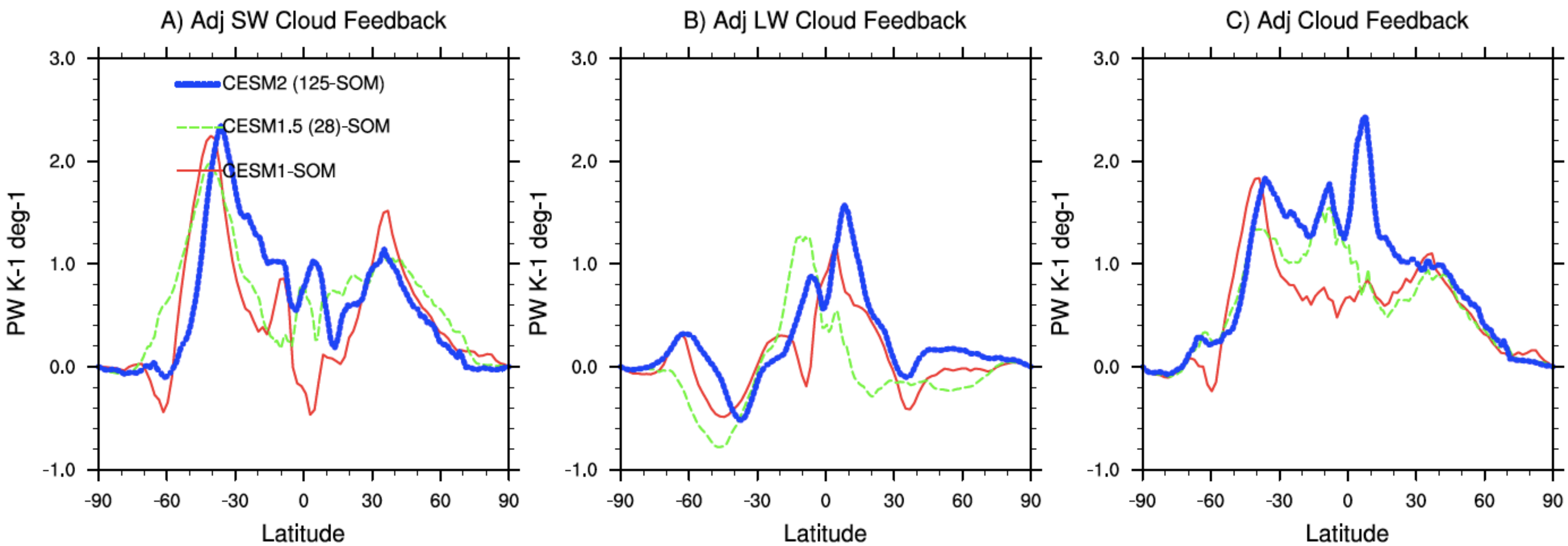
(Same as it ever was)



From SOM simulations

Cloud Feedback (Zonal Mean)

(Same as it ever was)



CESM2

CESM1.5

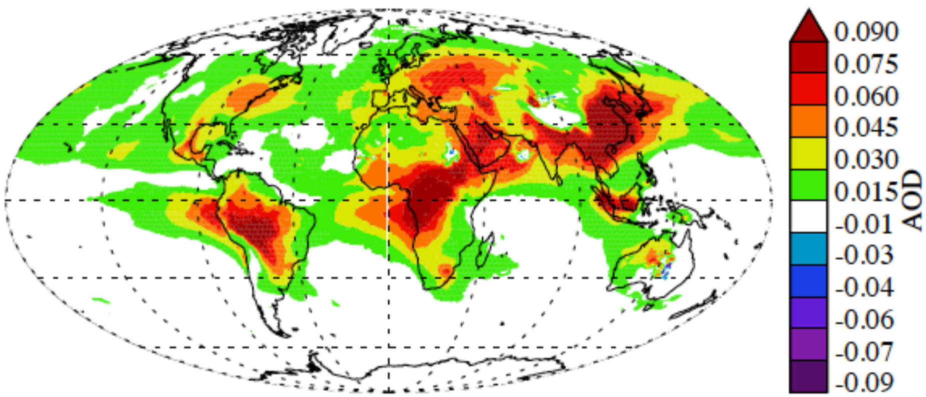
CESM1

Aerosol Forcing

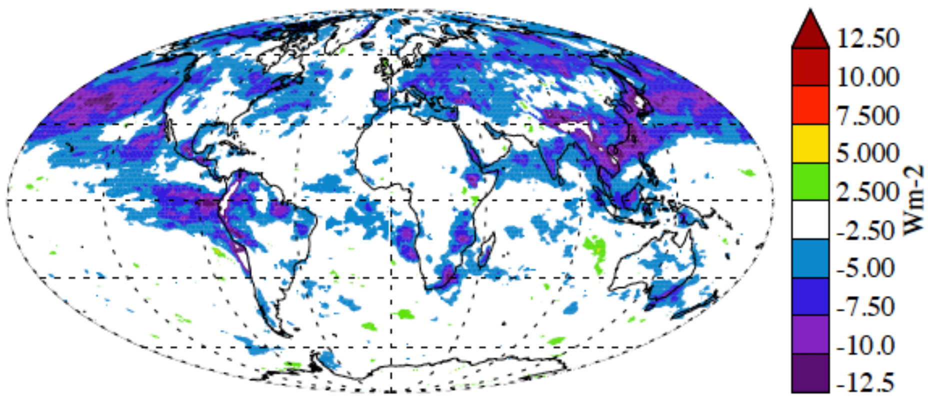
Run a model twice with different aerosol emissions (all else the same)

(Letting the days go by)

A) 2000-1850 ΔAEROD



B) 2000-1850 ΔTOA

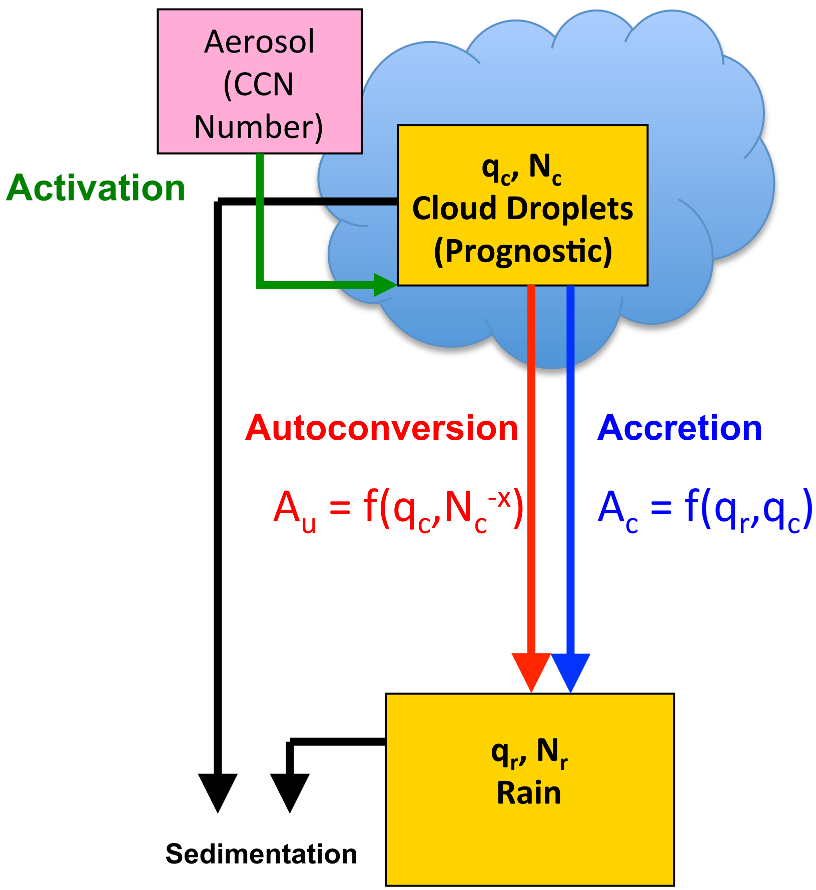


CAM6α ΔTOA (`125 series') = -1.6 Wm^{-2}
ACI -1.4Wm^{-2} , Direct effects -0.2Wm^{-2}

Updated from Gettelman et al 2010

Process rates: Essence

Key loss processes in bulk schemes are heavily parameterized
Goal is to represent stochastic collection process in 'pieces'



1. Activation $(\partial N_c/\partial CCN) = f(RH,w)$ Formation of cloud drops

2. Autoconversion $(\partial P/\partial N_c)$ Rain Formation (empirical)

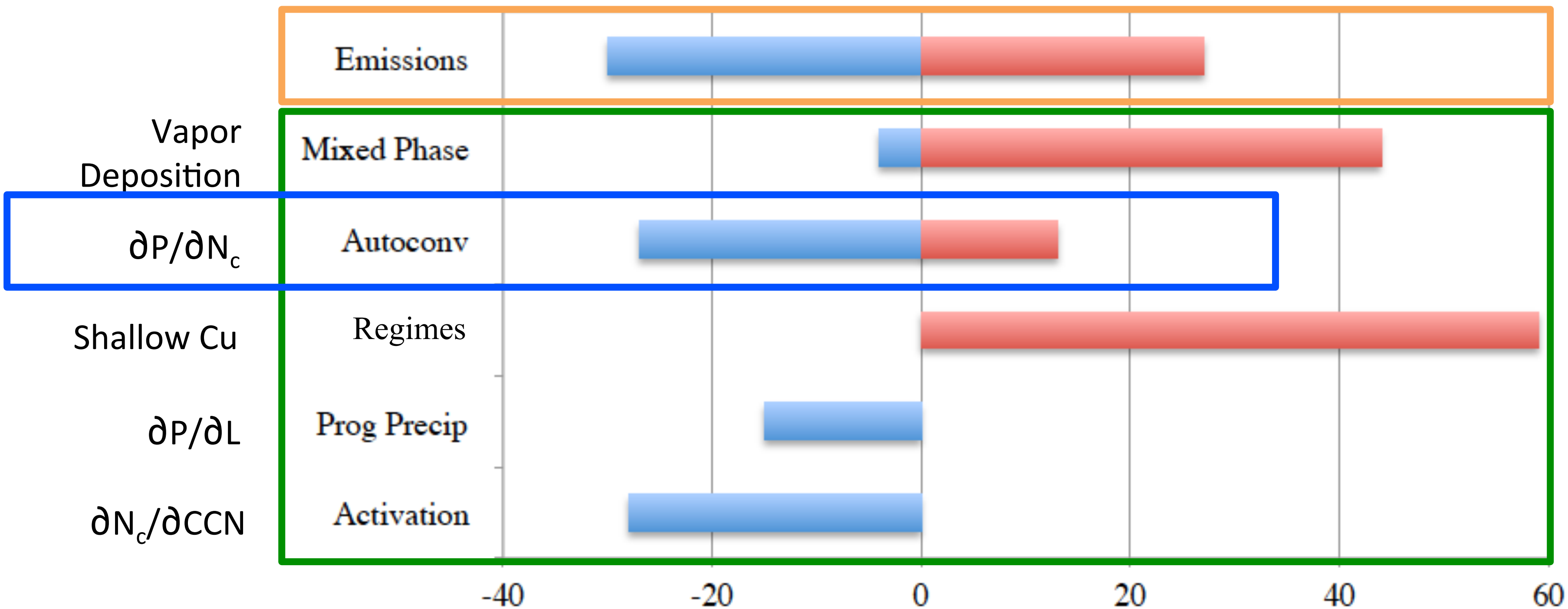
3. Accretion $(\partial L/\partial P)$: collection of cloud by rain (empirical)

Ac & Au represent the stochastic collection process (explicit with bin schemes)

CAM6 (CESM2) adds prognostic rain:

A. Better representation of q_r
B. Increase in A_c / A_u
C. Reduced ACI (reduced N_c effect)
Also change autoconversion (add hysteresis)

Uncertainty in Cloud Microphysics

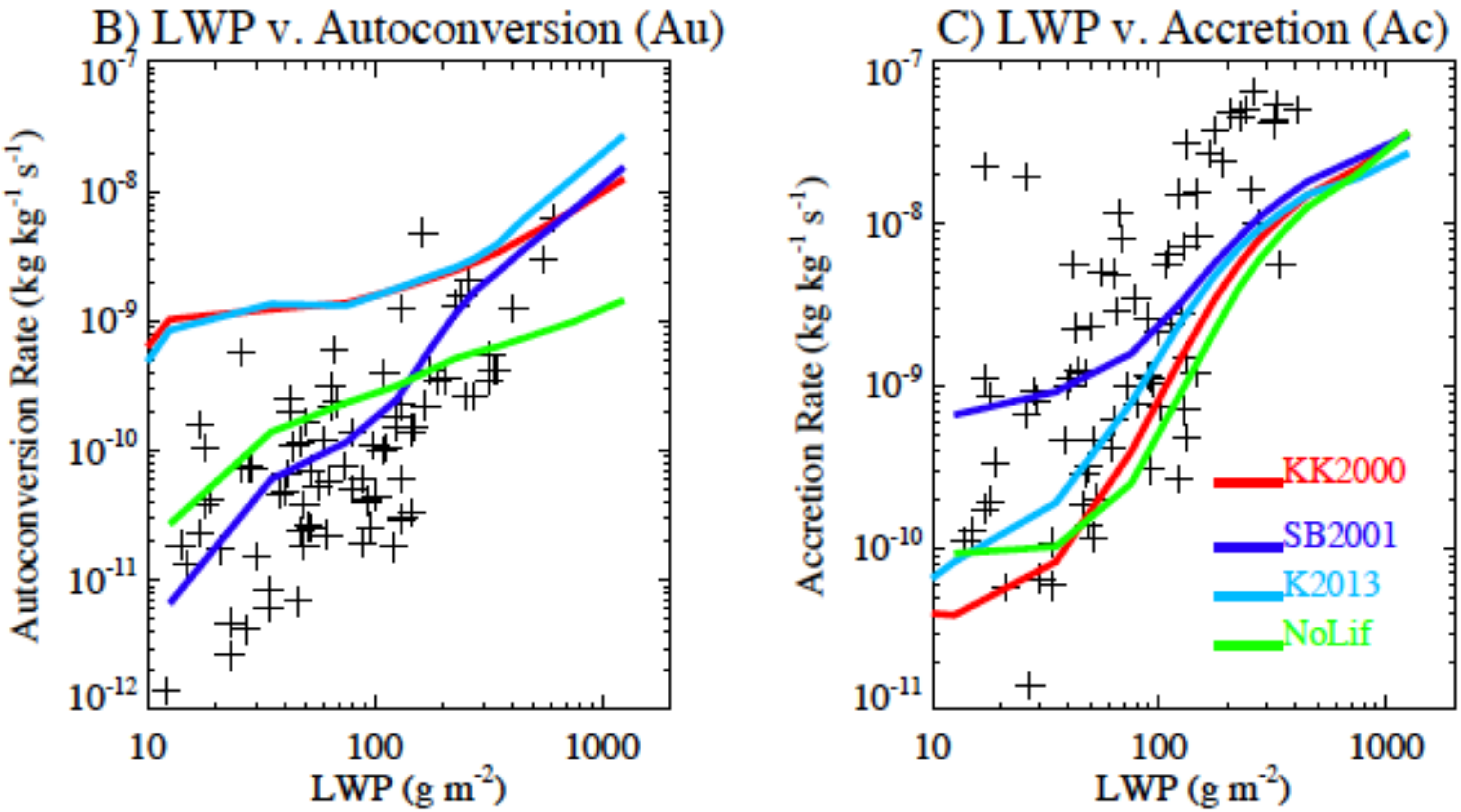


Emissions sensitivity: -30% to +30% (Similar to Carslaw et al 2013)
Cloud microphysics: -30% to +60%: due to Autoconversion, Mixed Phase, Regimes, Precipitation treatment

Gettelman 2015, ACP

Modifying Process Rates Using Observations

Liquid Water Path (LWP) v. Process rates



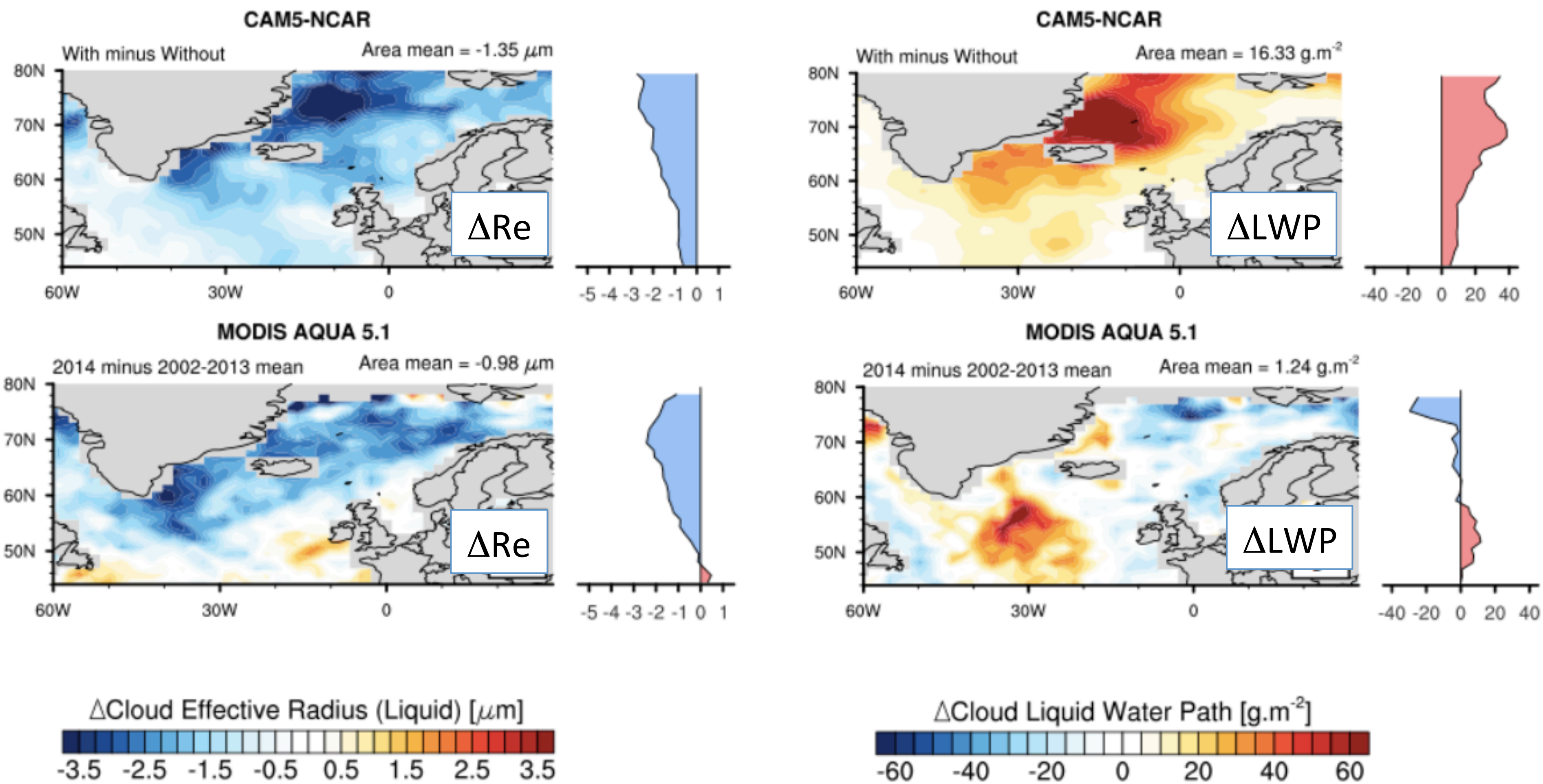
Gettelman, 2015, ACP
Data from VOCALS
(Terai & Wood 2013)

Results: Changed Autoconversion in CAM6, MG2
(from KK2000 to SB2001)

Still other processes to look at….

And you may ask yourself: Am I right or am I wrong? Comparisons with Observations

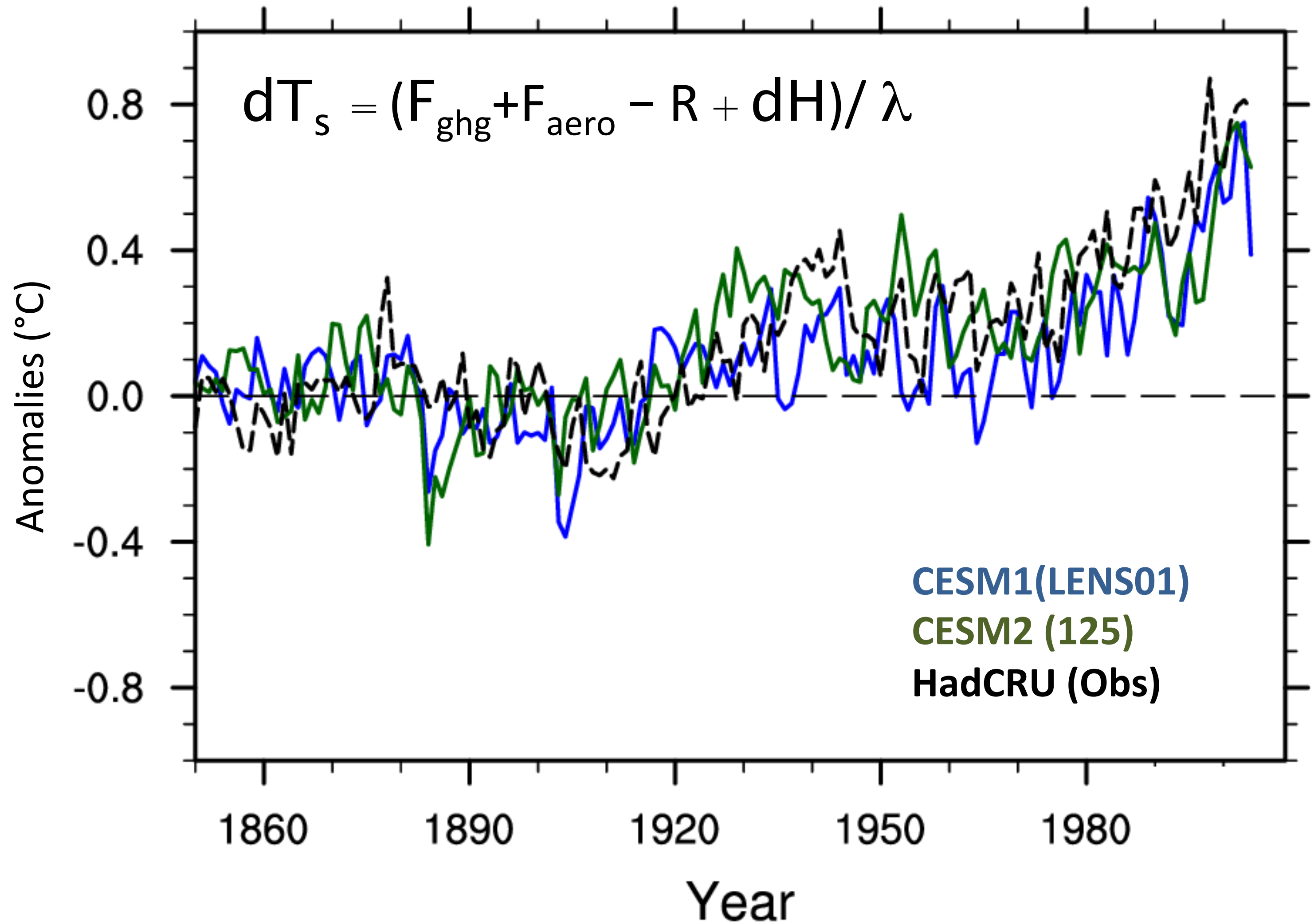
Holuhraun Eruption in Iceland, October 2014 - Climatology



20^{th} Century Global T_s Anomalies

Temperature anomalies from 1850-1899 average

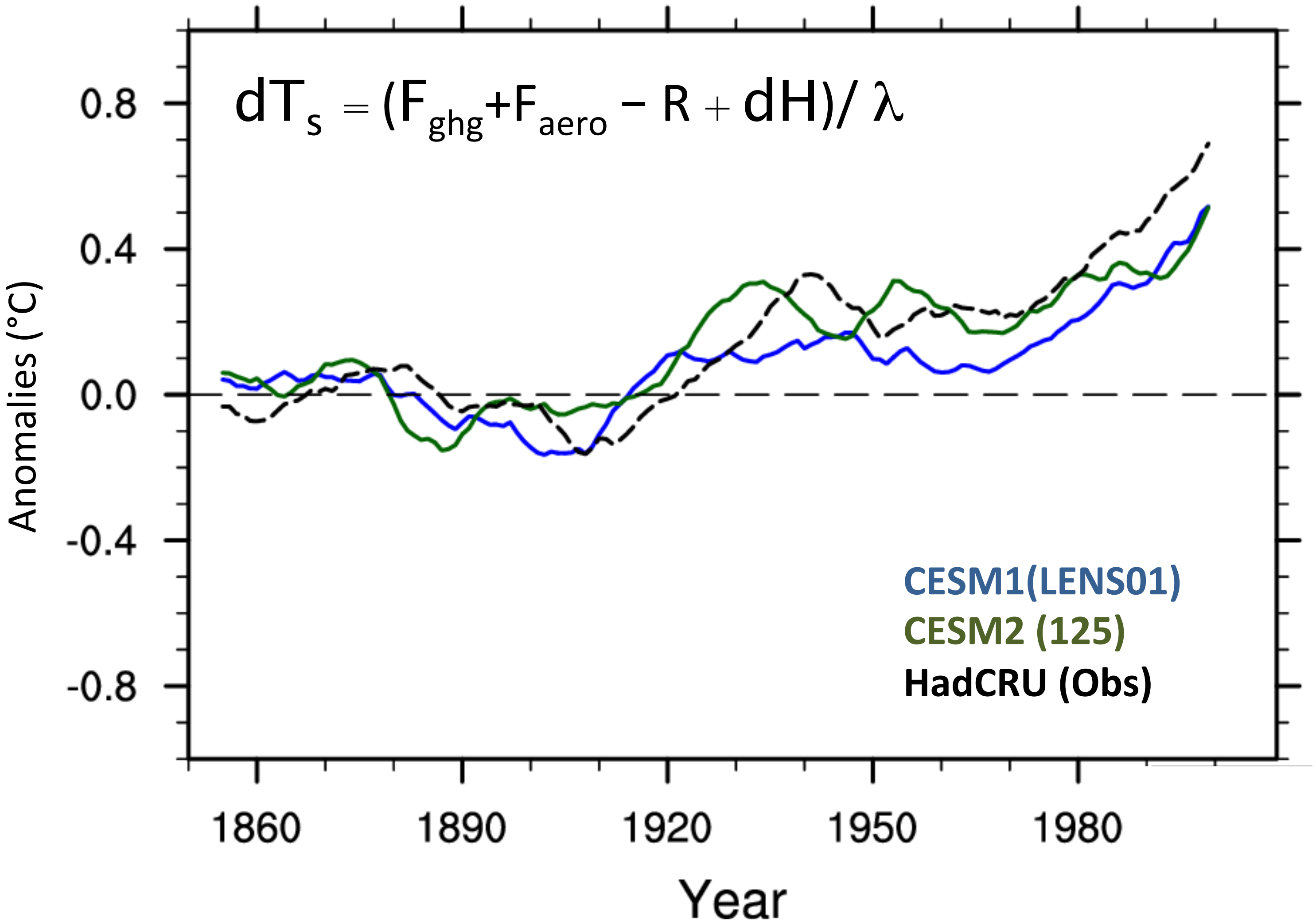
Letting the days go by…



20th Century Global T_s Anomalies

Temperature anomalies from 1850-1899 average

Where does that highway go to?



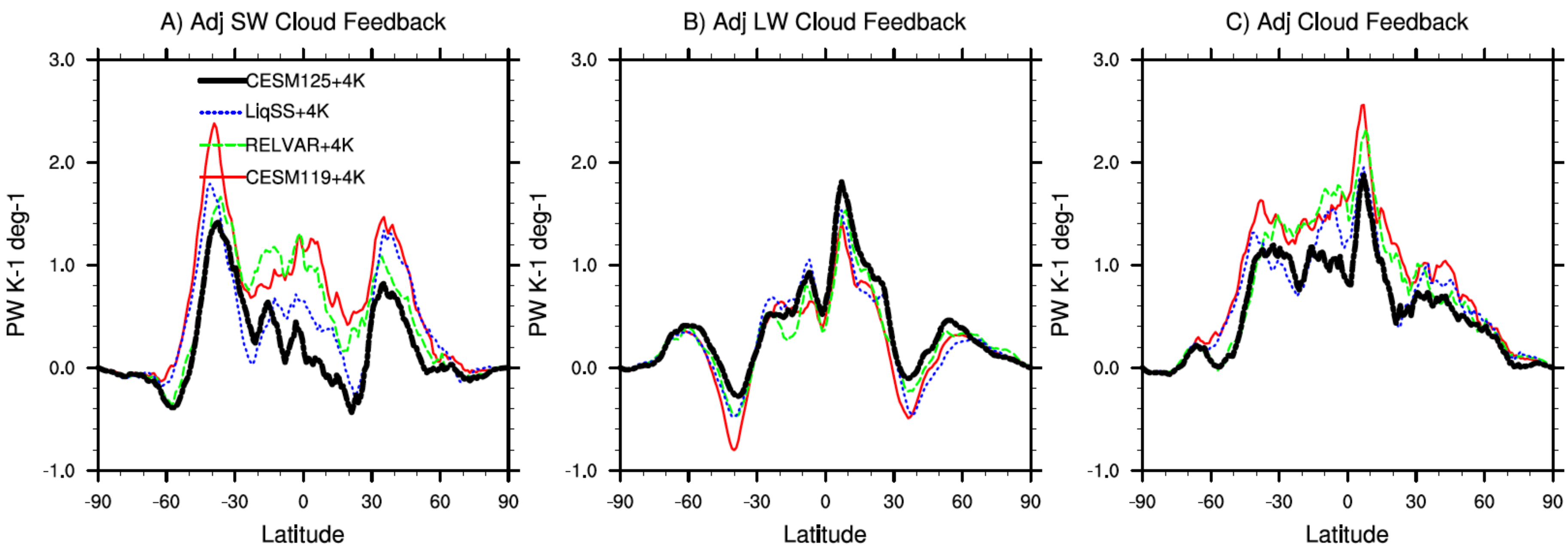
The road not taken
"This is not my beautiful house"

- Removing liquid supersaturation from CLUBB was done with an 'alternative' cloud scheme
  - This resulted in higher sensitivity
- Also, relative variance was left in with SB2001
  - This configuration was not appropriate for SB2001
- Produced a reasonable 1850 climate, but…

Same as it Never was….

Evolution of Cloud Feedback

SST+4K Experiments (Fixed SSTs)



Current CESM2 (125)

Add Liquid Supersaturation (LiqSS) subtropical increase

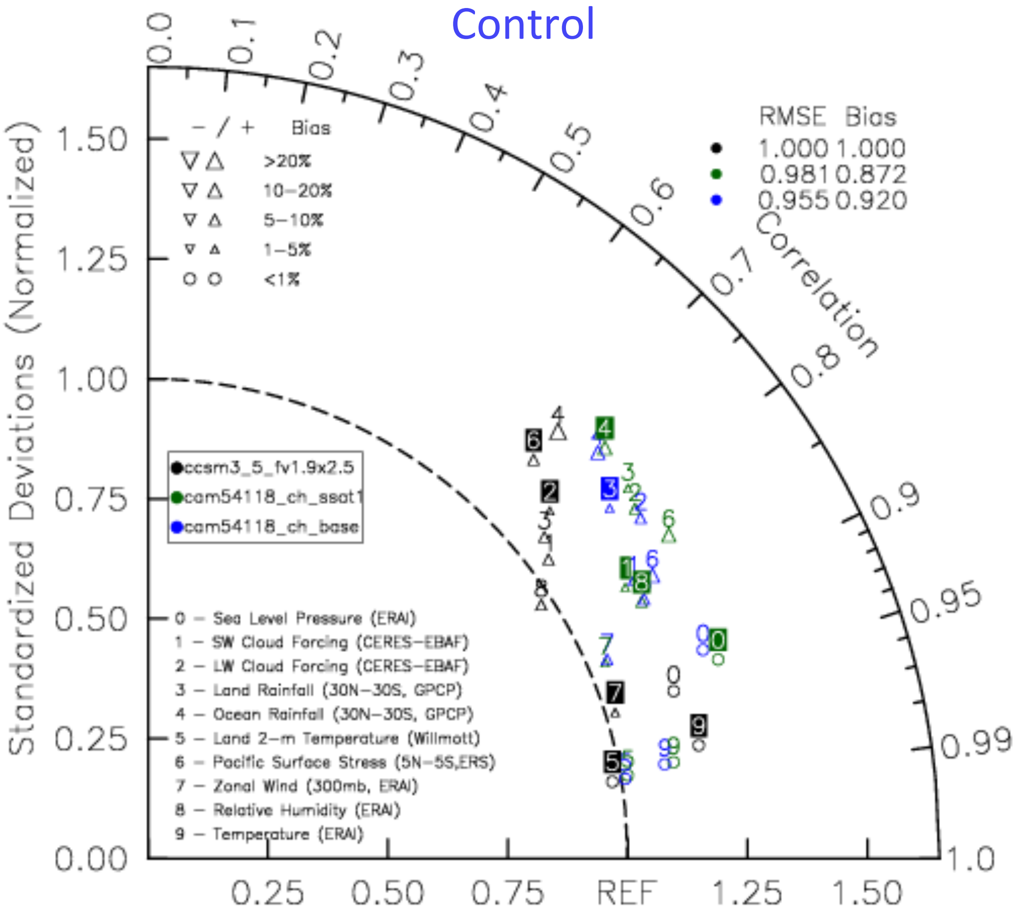
Add back Relative Variance (RELVAR) extra tropical increase

CESM1.5 (119): 'High' Sensitivity

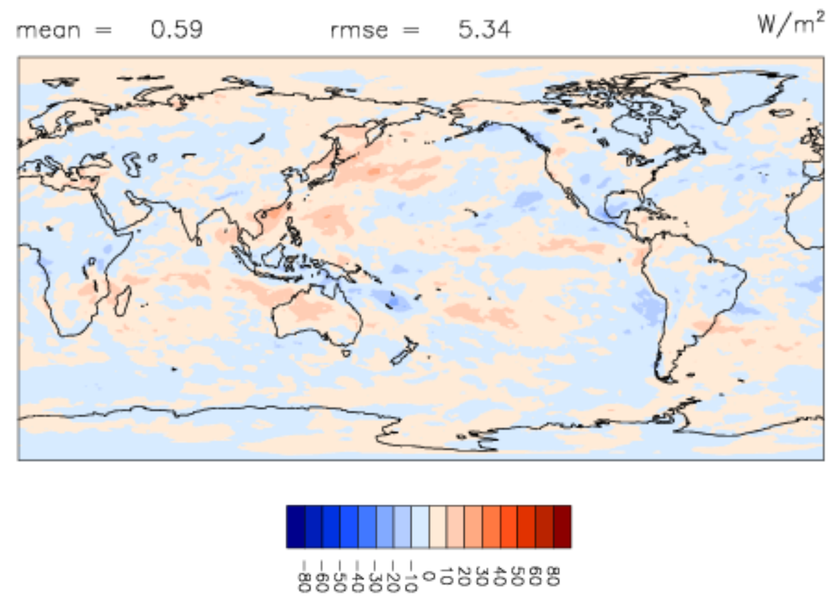
Models are equally skillful

And you may ask yourself
Am I right? Am I wrong?

Reference
High Sensitivity
Control



Modified - Control



How do you discriminate models?

Summary: *How did I get here?*

- CESM2 Atmosphere (CAM6) is much improved *(a beautiful house!)*
  - Thanks to observations
  - Arctic is still an open question, many biases, not sure of observations
- Climate Feedbacks in CESM2 similar to CESM1 *(Same as it ever was)*
  - Water vapor, albedo, clouds
  - Equilibrium climate sensitivity (ECS) CESM2 ≈ 3.9K (CESM1≈4K)
- Aerosol Forcing: Increased, then reduced *(Same as it ever was)*
  - Added new regimes (shallow convection)
  - Adjusted cloud microphysics
  - Hard to compare to observations
- High sensitivity configuration 'equally probable' *(not my beautiful house)*
  - Will analyze and investigate further
- Note: the 20th century is potentially a constraint (Letting the days go by)
  - We might have changed the model if it was not acceptable
- Heat budget analysis (Trenberth) indicates CESM2 has a lower 'H' (Ocean Heat Uptake) than observed. Also lower R (TOA imbalance).
  - Forcing is too weak? *(you may find yourself living in a shotgun shack)*

Thanks!

- CESM Team
- David Byrne, Brian Eno…